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COMBUSTION-ENGINE TEMPERATURES BY THE
SODIUM LINE-REVERSAL METHOD

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SUMMARY

The sodium line-reversal method has been used in some preliminary measurements of flame temperature. Improvements in the method involving a photographic recorder and a means of correcting for the dirtiness of the windows are described. The temperatures so obtained are compared with those calculated from pressure diagrams.

INTRODUCTION

There has been a great deal of argument for and against the validity of the sodium line-reversal method of measuring flame temperature. The work described in the subject paper is not concerned with this argument but is confined to apparatus and results on the assumption that the validity of the method has been established. A great many published articles deal with various methods and their merits and results. A complete bibliography of the available information is given in reference 1.

APPARATUS AND METHOD

A single-cylinder N.A.C.A. 4-cycle test engine connected to a dynamometer was used. The engine is fitted with a dual carburetor and with auxiliary equipment for measuring the quantity of air and fuel. Spark-plug openings in the cylinder make it possible to fire the engine from any one of five points around the circumference or from one point in the center of the head. Two ignition coils operated by the engine timer were available. Figure 1 is a photograph of the actual set-up and figure 2 is a diagrammatic sketch of the temperature-measuring apparatus.

At the right are the source light, which is a "point-source," and the optical pyrometer for measuring the brightness temperature of the source. The light from the source is collimated by a lens placed with its principal focus at the source. The parallel beam of light passes through two fused quartz windows in opposite sides of the cylinder to a second lens, which focuses the image of the source light on the slit of the spectrometer. The spectrometer is a Bausch and Lomb constant-deviation type. A special film drum driven at half crankshaft speed was mounted on the spectrometer so that the film opposite the slit in the film drum was at the focal position for the D lines of sodium. It was possible to move the film drum in such a manner that several exposures could be made on the same width of film. The circumference of the drum is 10 inches and the width $2\frac{1}{4}$ inches. The width of spectra exposed was approximately $\frac{1}{4}$ inch. The slit in front of the film is $\frac{1}{16}$ inch. Since 10 inches of film corresponds to 2 revolutions of the crank, 10 inches is 720° of crank angle and $\frac{1}{16}$ inch corresponds to 4.5° of crank angle. This value can be arbitrarily changed over considerable limits, depending upon the resolution of crank angle desired. Obviously the required time of exposure will have to be appropriately adjusted. Superspeed panchromatic film was used.

The same part of the cycle was repeatedly superimposed at the same position on the film, since the film drum turned at half crank-angle speed. The film drum used in the photographic method took the place of the stroboscope customarily used in the visual method. The fact that the sodium lines on the revolving drum record are resolved and unblurred is sufficient evidence of the perfect alinement of the drum. Timing was put on the film by a spark from the ignition system of the engine; i.e., when the charge was fired, the previously mentioned second ignition coil produced a spark that marked a spot on the film. When the film drum was not rotating, this trace was approximately $\frac{1}{16}$ inch in length; but when the drum was rotating, the trace increased to about $\frac{1}{8}$ inch in length. This variation was traced to the variation in firing that is inevitable with a spark-ignition arrangement. The engine was run at several speeds and there was never any indication of variations due to the flexible drive shaft. This condition is reasonable as the film drum was very light and the flexible shaft very strong so that the film drum should follow very closely the rotation of the crankshaft.

The literature is singularly unenlightening on the means of correcting for the dirtiness of the windows. In a visual method with a stroboscope, dirty windows would be especially troublesome. In the photographic method, dirty windows are disagreeable but it is possible to correct for the apparent change in temperature of the source light so that the results do not depend upon the assumption that the windows are either as clean as at the start or as dirty as at the end of the run.

The correction was made by developing what are designated as "dirtying curves." The engine was warmed up and adjusted to fuel mixture and temperature and the window near the source lamp was put into position. The engine was run for a definite time interval after which the window was removed. The window was then attached to the front of the optical pyrometer and the effective temperature of the source light was measured for several conditions of current consumption of the source light. Each such run gives one point on each of the dirtying curves. By the use of the resulting series of curves, such as those of figure 3, the currents through the source light necessary to determine the time intervals to give the desired effective temperature may be chosen. After a set of curves has been developed, a schedule such as table I may be prepared and, with the engine adjustment unchanged and the engine properly warmed up, be followed for the run. The windows are checked with the optical pyrometer before each cleaning and it is determined whether the effective temperature is the expected value. If the point does not fall on the expected curve, it is immediately apparent that the engine did not operate as it did during the original calibration and the results are consequently useless.

The temperatures at which the source light operates and the time of exposure are matters of experience and of the engine-temperature range to be covered.

Figure 4 shows the actual record run from table I. Unfortunately, spectra never reproduce very satisfactorily and one should not expect that the points of reversal may be picked out from the reproduction with anything like the precision possible from the original film.

After the record has been obtained, it is only necessary to determine the crank angle at which the reversal occurred. There are two such points for each temperature of the source light: one as the temperature in the cylin-

der is rising, as combustion starts, and the other as the temperature is decreasing on the expansion side of the stroke.

The point of reversal can be picked to within $\pm 2^\circ$ of crank angle and the temperature is probably accurate to $\pm 25^\circ$ C. Although the pyrometer can repeatedly be set much more accurately than $\pm 25^\circ$ C., there is an effective change in temperature of the source light during the time of exposure that probably results in a total error of $\pm 25^\circ$ C. The optical pyrometer is calibrated at frequent intervals against a standard ribbon-filament lamp. The correction due to the absorption of the collimating lens and the correction for the optical pyrometer when it is used to give brightness temperature at $\lambda = 5890 \text{ \AA}$ instead of at 6500 \AA have been neglected inasmuch as they are of opposite sign and of the same order of magnitude.

DISCUSSION

Flame-temperature curves calculated from the sodium line-reversal method and from an analysis of the pressure diagram are presented in figure 5. A casual inspection emphasizes the differences more than the points of agreement. The lack of agreement over the first part of the cycle is accounted for by the fact that the flame started from the position of spark plug 3 (see fig. 2) and crossed the line joining the two windows before any appreciable part of the mixture in the cylinder had burned. It is quite obvious that the line-reversal method will indicate the temperature of this flame while the pressure indicator will record very little pressure rise. In the latter part of the cycle there is better agreement than can be expected or than generally exists. The results of several tests, however, show good agreement, usually not differing by more than $\pm 50^\circ$ C. The line-reversal method generally gives the higher temperature. The discrepancy may be due to the fact that the temperature is measured across a diameter of the combustion cylinder and records more nearly a maximum than an average temperature or be due to a slight amount of smoke, which would lower the effective temperature of the source light and thereby give too high a temperature.

Further tests are planned in which a new cylinder head will be used to study local temperatures. With this arrangement it should be possible to measure the tempera-

ture at several positions ahead of and behind the flame front. This method appears to be one way of investigating the temperatures connected with detonation and of learning more about phenomena ahead of and in the flame front. For the investigation of average temperature, rather than of local temperatures and combustion phenomena, however, pressure diagrams are more satisfactory.

The effect of the luminosity of the flame is often mentioned. Figure 6 shows a record for various intervals of time taken without the source light. It is perfectly clear that there is no flame luminosity to cause trouble.

CONCLUSIONS

The improved photographic method of measuring combustion engine temperatures has the advantages of high accuracy and speed of action. Accuracy is obtained by the application of a correction for dirty windows, by high resolution of crank angle, and by elimination of personal errors.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 25, 1936.

REFERENCE

1. Rassweiler, Gerald M., and Withrow, Lloyd: Flame Temperatures Vary with Knock and Combustion-Chamber Position. S. A. E. Jour., April 1935, pp. 125-136.

TABLE I
Schedule of Test Run

Run	Current through source light	Time		Effective temperature
		Start	End	
	Amperes	Seconds	Seconds	°C.
1	1.99	25	28	2375
2	1.99	45	50	2325
3	1.80	65	75	2240
4	1.24	90	110	2040
5	1.80	125	135	2160
6	.75	150	240	1730

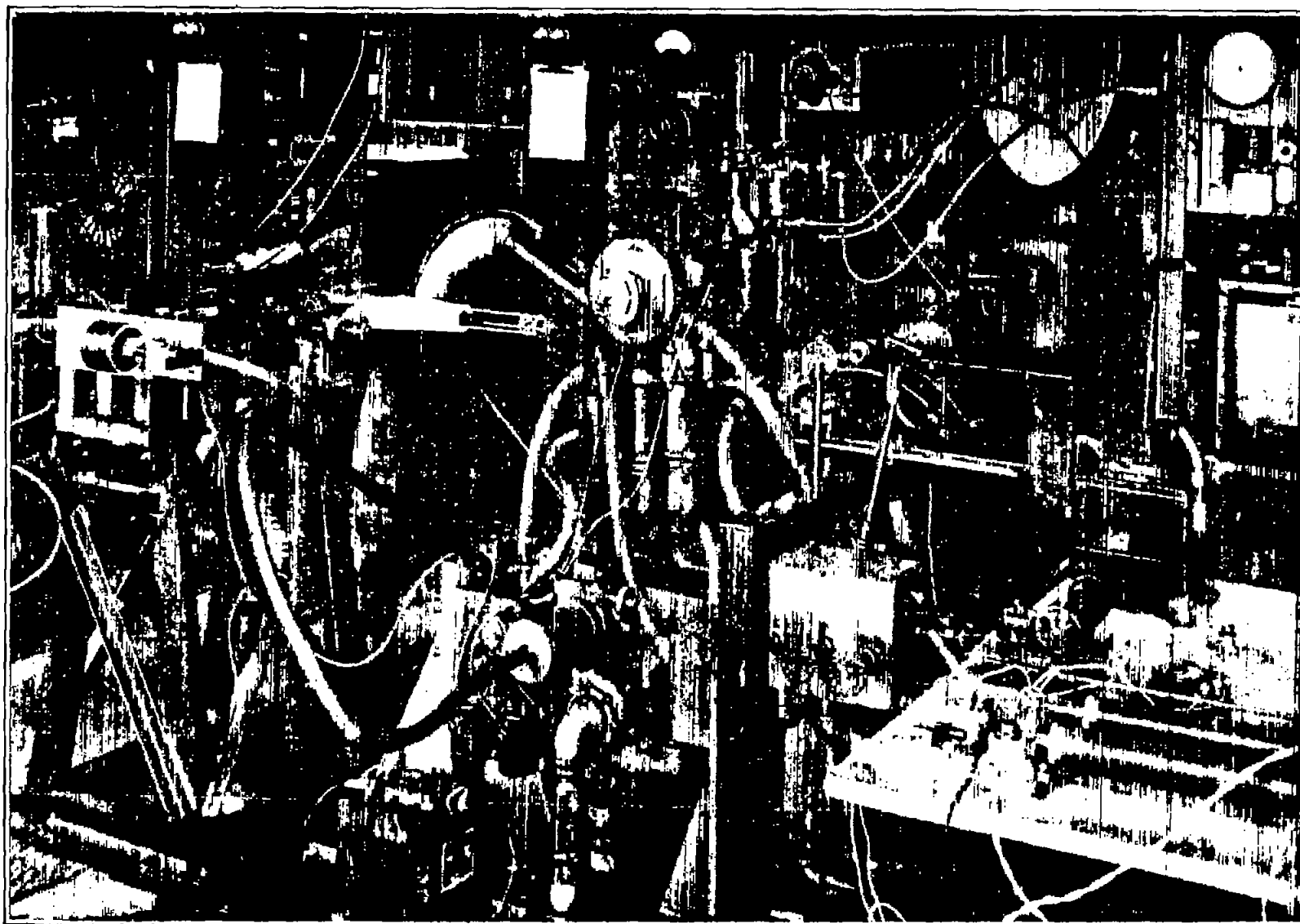


Figure 1.- Set-up for measuring flame temperature

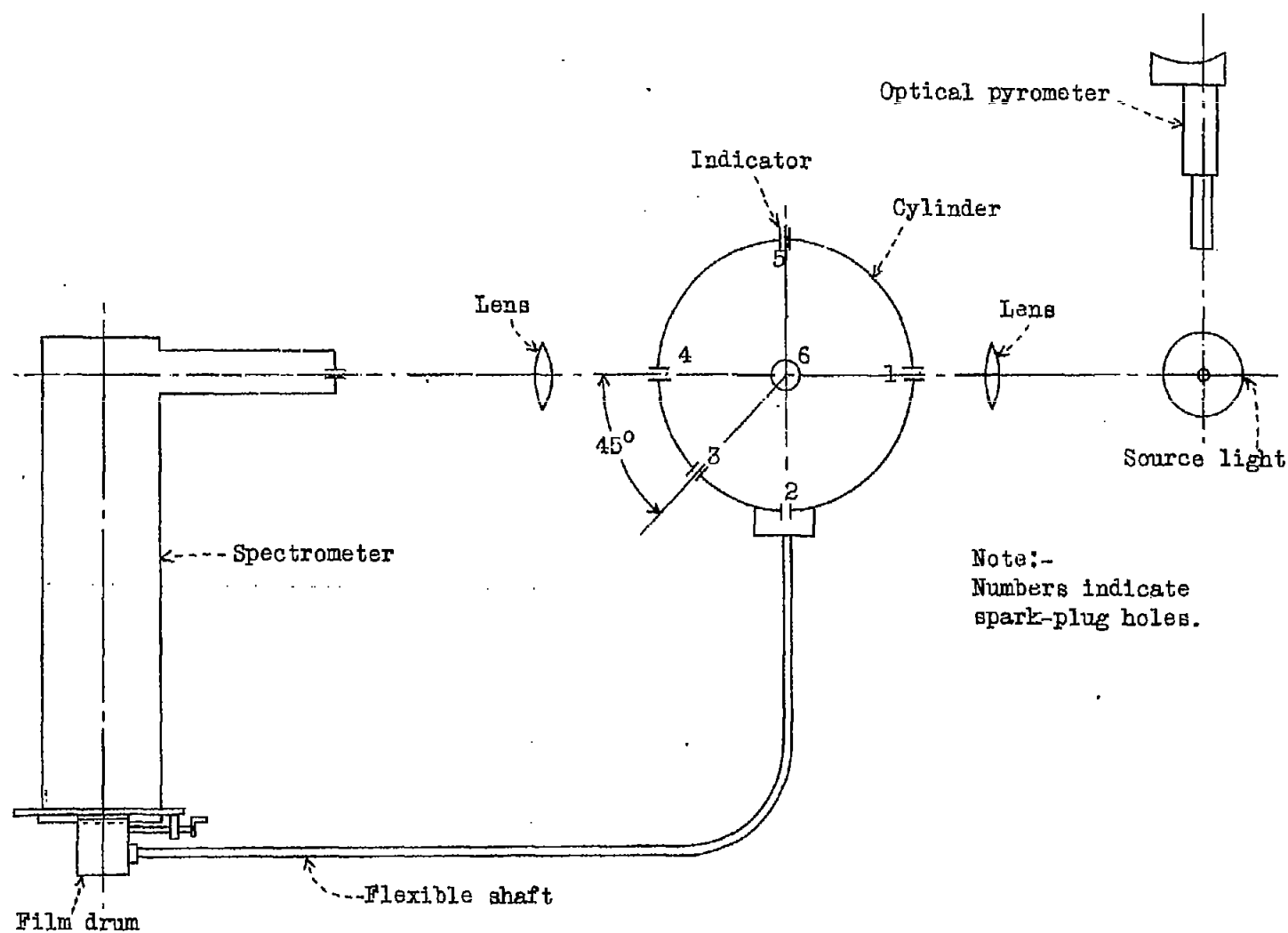


Figure 2.- Diagrammatic sketch of the flame-temperature-measuring apparatus.

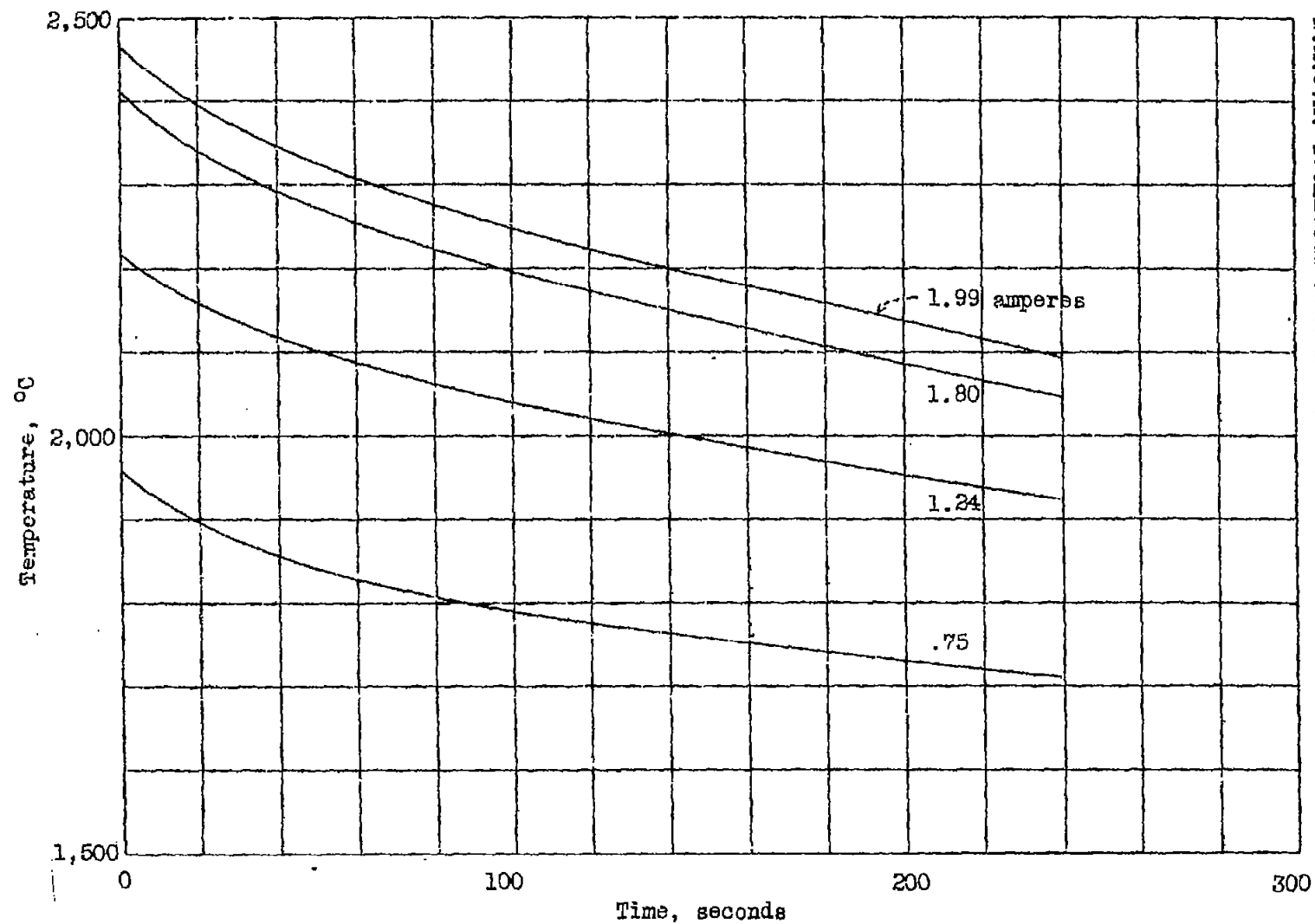


Figure 3.- Dirtying curves.

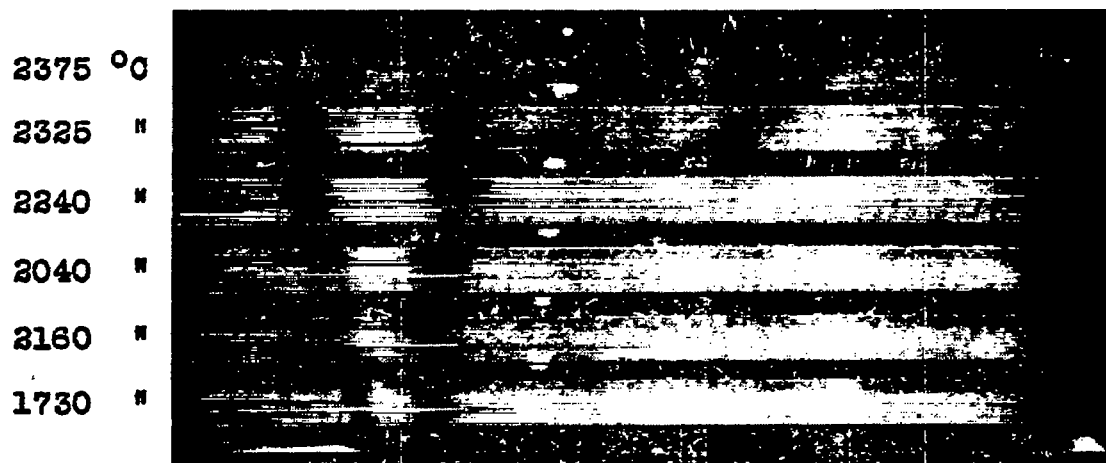


Figure 4.- A sample record of a flame-temperature run.

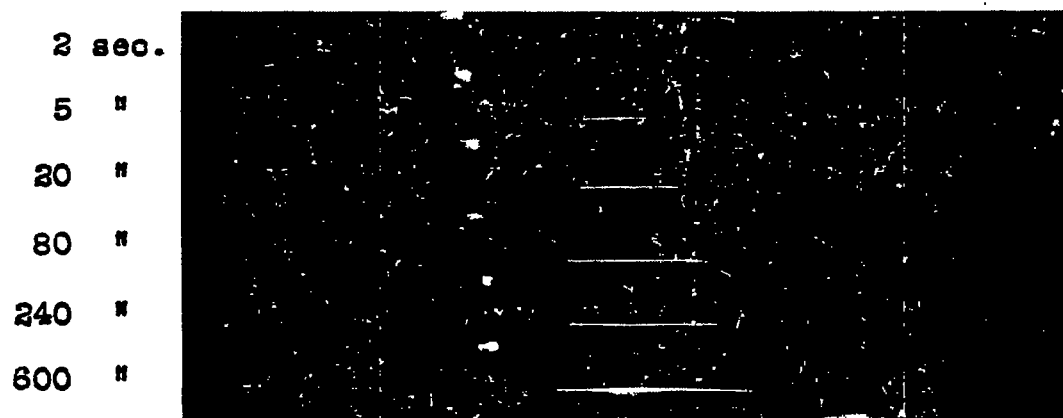


Figure 6.- Record taken without the source light

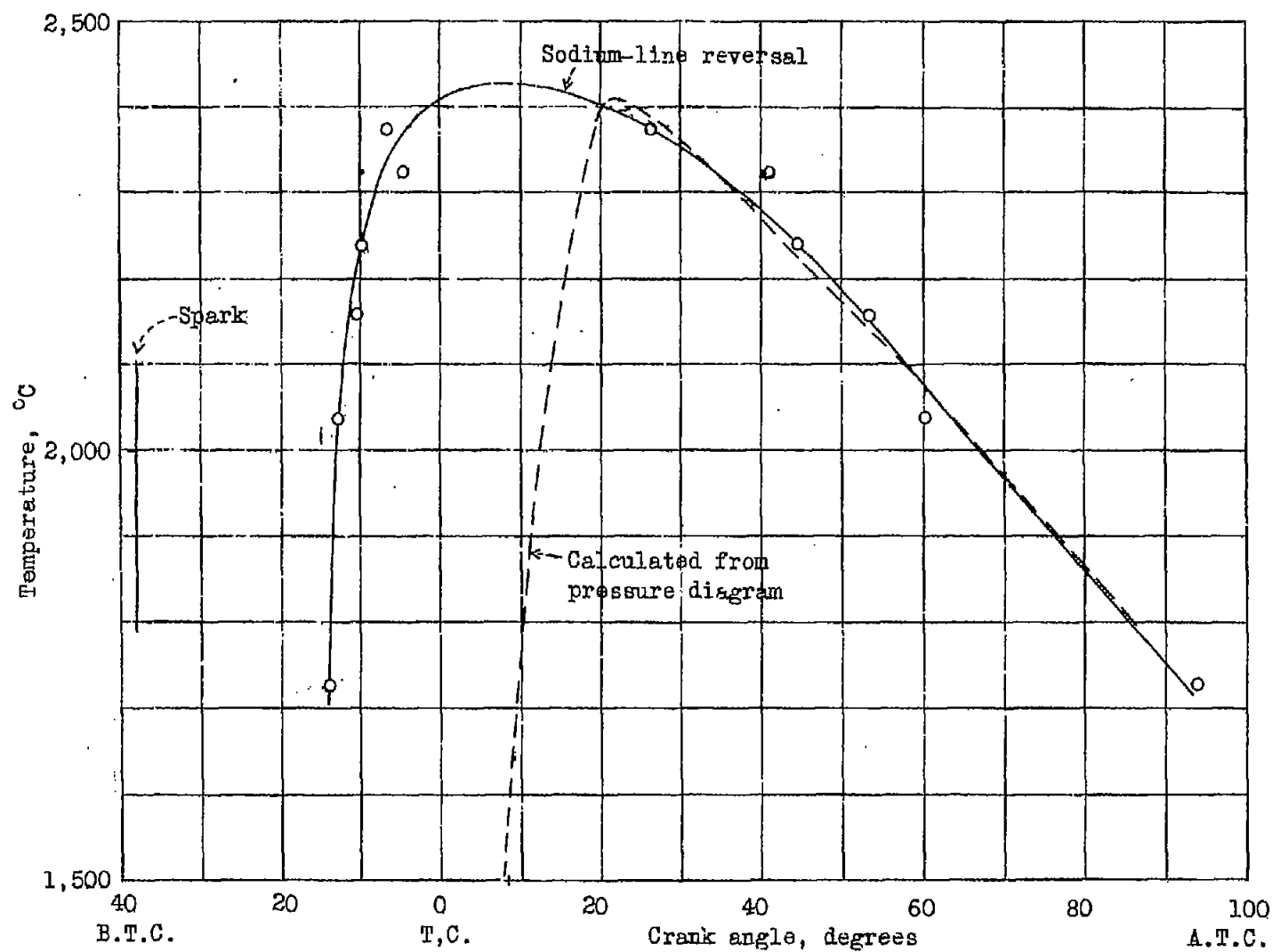


Figure 5.- Flame temperatures against engine crank angle.